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RAD-B117-264

ANALYSIS OF THE SCOUT R-4 HEAT SHIELD FLIGHT TEST DATA

By E. Offenhartz, J. A. Collins, and H. Hurwicz

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
Hampton, Virginia

22 December 1964

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AVCO CORPORATION
Wilmington, Massachusetts

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ILLUSTRATIONS

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1.0 INTRODUCTION

The analysis of the Scout R-4 Flight Test was based on the preliminary information supplied by NASA in a Langley Working Paper (ref. 1). This reference represents a complete and extremely valuable set of data originating from a very successful flight test.

The objective of the Avco data interpretation program was:

1. Determination of the Avcoat 5026-HC/G heat shield material performance.

2. Determination of the impact of the flight test results on the Apollo heat shield design.

With the above objectives in mind, the following approach was adopted:

1. The ground test information pertaining to the material characterization and performance was reviewed. This included: (a) the material properties and ablation characteristics review; and (b) experimental verification by means of ground simulation of flight trajectory of the two theoretical models of ablation and heat conduction used in performance predictions.

2. The flight test ablation and char recession sensor data through the period of their functioning were examined and compared with the standard design techniques used for predictions.

3. The flight test temperature sensor data were examined in two phases:

   a. Throughout the period of ablation sensor functioning where simultaneous prediction of recession and temperature response is feasible and amendable to comparison with flight information.

   b. After the ablation sensors stopped functioning when the above comparisons are less amenable to simultaneous ablation and temperature response analysis.

This division into two phases has the further merit, in that the comparison of Apollo and Scout flight environment is more meaningful during the first phase. In the second the environments differ radically, the Scout environment being much more severe than Apollo.

4. The upper bound of the recession as inferred from the temperature sensor data was assumed, and theoretical postulates were made to interpret the feasibility of such occurrence; and finally

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5. On the assumption that the upper bound was indeed achieved in however unexplainable fashion, the flight data were factored into Apollo heat shield design to determine the design change requirements if any.

In the interpretation of the flight test data, it is necessary to emphasize the need for simultaneous treatment of the ablation (recession) and temperature response to arrive at meaningful conclusions relative to the material performance. The effect of the flight environment on the material performance must also be taken into account when applying results from a particular flight to another vehicle to be exposed to a vastly different set of environmental flight conditions.

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2.0 BACKGROUND DATA

2.1 HEAT SHIELD MATERIAL PROPERTIES AND CHARACTERISTICS

The basic requirement for proper utilization of the heat shield design models is the knowledge of the thermal and optical properties and ablation characteristics. These properties and characteristics have been evaluated in Avco ground test facilities for conditions applicable to Apollo. A summary of the thermal properties as used in the Design Model is given in table I. It should be noted that thermal conductivity as used in the Design Model is a function of temperature which reflects the material charring characteristics. Surface temperature is selected as a function of the heat flux. For the Scout vehicle, ablation temperatures (selected for preflight evaluations) of 4000 and 4500°F were believed to bracket the actual surface temperature. The ablation characteristics for Avcoat 5026-39/HC-G are also shown in table I.

TABLE I

DESIGN PROPERTIES FOR AVCOAT 5026-39/HC-G	
Density, lb/ft^3	30.8
Thermal Conductivity, BTU/hr-ft-°F	0.058 Virgin Material
	0.12 Fully Charred
Specific Heat, BTU/lb-°F	0.35
Emissivity	0.75
Ablation Temperature, °F	4,000 lower limit
	4,500 upper limit
LAMINAR ABLATION CHARACTERISTICS	
Transpiration Coefficient	0.997
$H_v + Cp \Delta T$	-442.0
TURBULENT ABLATION CHARACTERISTICS	
Transpiration Coefficient	0.359
$H_v + Cp \Delta T$	1209.0

[redacted]

The laminar test data were obtained in the Avco Model 500 arc facility. The turbulent data were obtained in the Avco 10 Mw arc facility and represent shear values ranging from about 4 to 13 lb/ft^2.

2.2 HEAT SHIELD ANALYSIS ACCURACY

The accuracy of the heat shield design process cannot be rigorously evaluated for real materials in transient ablation conditions. However, a good indication of the accuracy of heat shield design procedure can be obtained by comparing predicted and measured surface recession and temperature data for controlled, carefully conducted ground tests. This type of comparison has been completed repeatedly at Avco RAD using the OVERS arc facility which is capable of achieving heat fluxes ranging from 5 to 300 Btu/ft^2-sec for stagnation enthalpy conditions ranging from 7000 to 20,000 Btu/lb.

Examples of the correlation between predicted and measured values are shown in figures 1 and 2. Figure 1 shows the results of a constant heat flux test. Predictions for the Design Model (Program 1327) are shown as dashed lines; the solid lines are corresponding predictions obtained from the Avco RAD Charring Ablation Model (Program 1600) (ref. 2). The symbols indicate temperature as measured by thermocouples. In general, the Design Model temperature predictions are higher than the Charring Ablation Model predictions which are, in turn, in good agreement with the measured values or slightly higher. Similar correlations (with similar agreement) have been obtained from heat fluxes ranging from 20 to 270 Btu/ft^2-sec and for stagnation enthalpies of 10,000 and 20,000 Btu/lb. The fact that predicted values exceed measured values is of course a conservative feature considering the backface temperature response as a design criterion.

To evaluate the effect of a transient heat pulse and enthalpy on the accuracy of the two analytical models, a five-step (in both heating and enthalpy) trajectory simulation was devised for an OVERS test. Although it was not possible to obtain a perfect match of the reentry heat flux and enthalpy histories, a very good simulation of HSE-3A was produced for Apollo body station 300, the aft most location on the windward meridian of the crew compartment. The comparison of analytical predictions and experimental measurements of temperature and surface recession from this simulated entry case are shown in figure 2. It can be seen that for all depths the Design Model over-predicts the temperature response. Except for those thermocouples at 0.30 and 0.50 inch, the Charring Model is also conservative for all depths. Since this was the first successfully completed test of this type, the test technique has not been perfected. It is believed that analysis of future tests, where better control and calibration have been obtained, will show even better agreement at all thermocouple depths. The Charring Ablation Model is also being improved, as more information on the required parameters is factored into the analysis.

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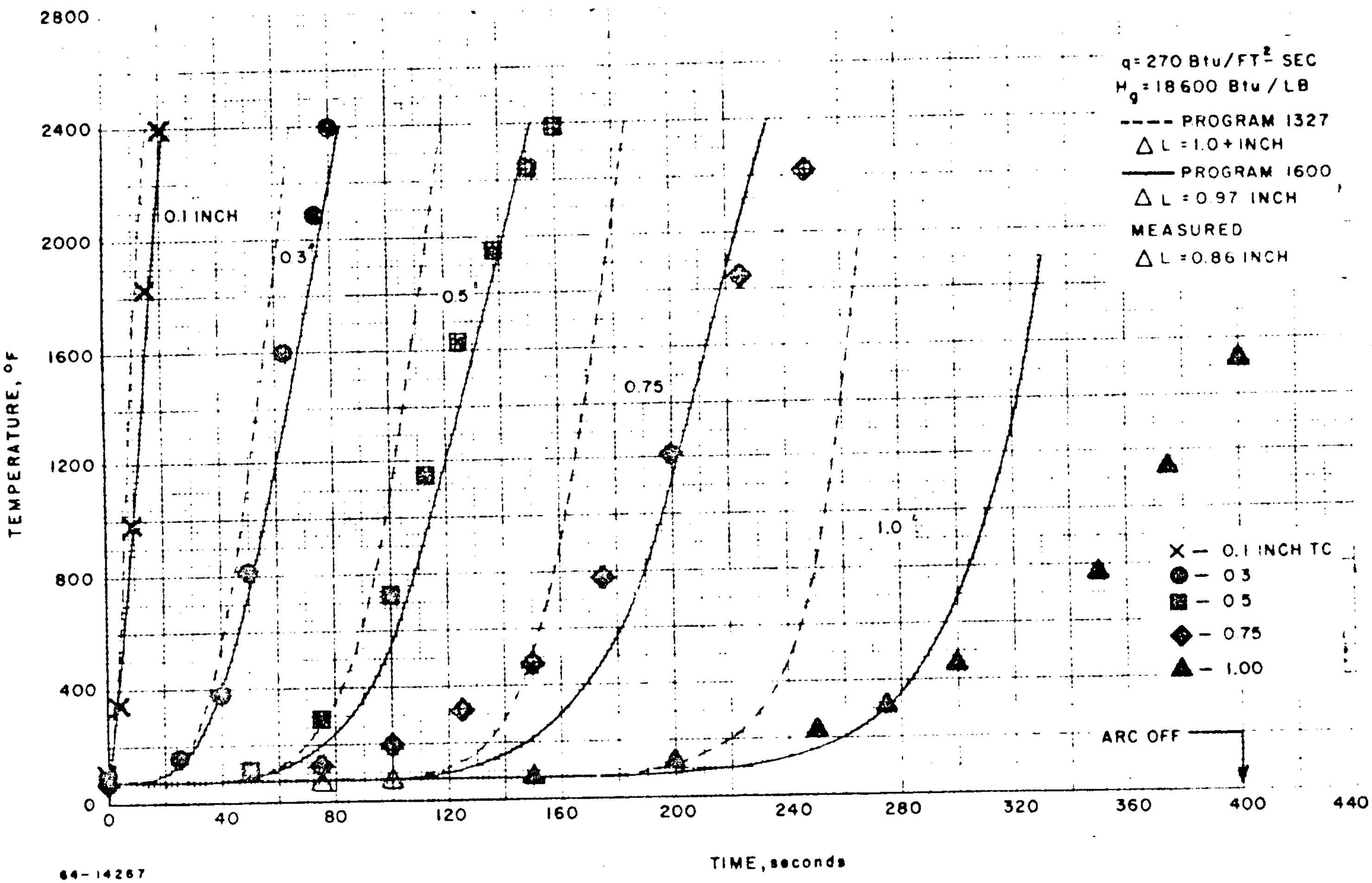

Figure 1 COMPARISON OF TEMPERATURE HISTORIES, AVCOAT 5026/39 HC-G
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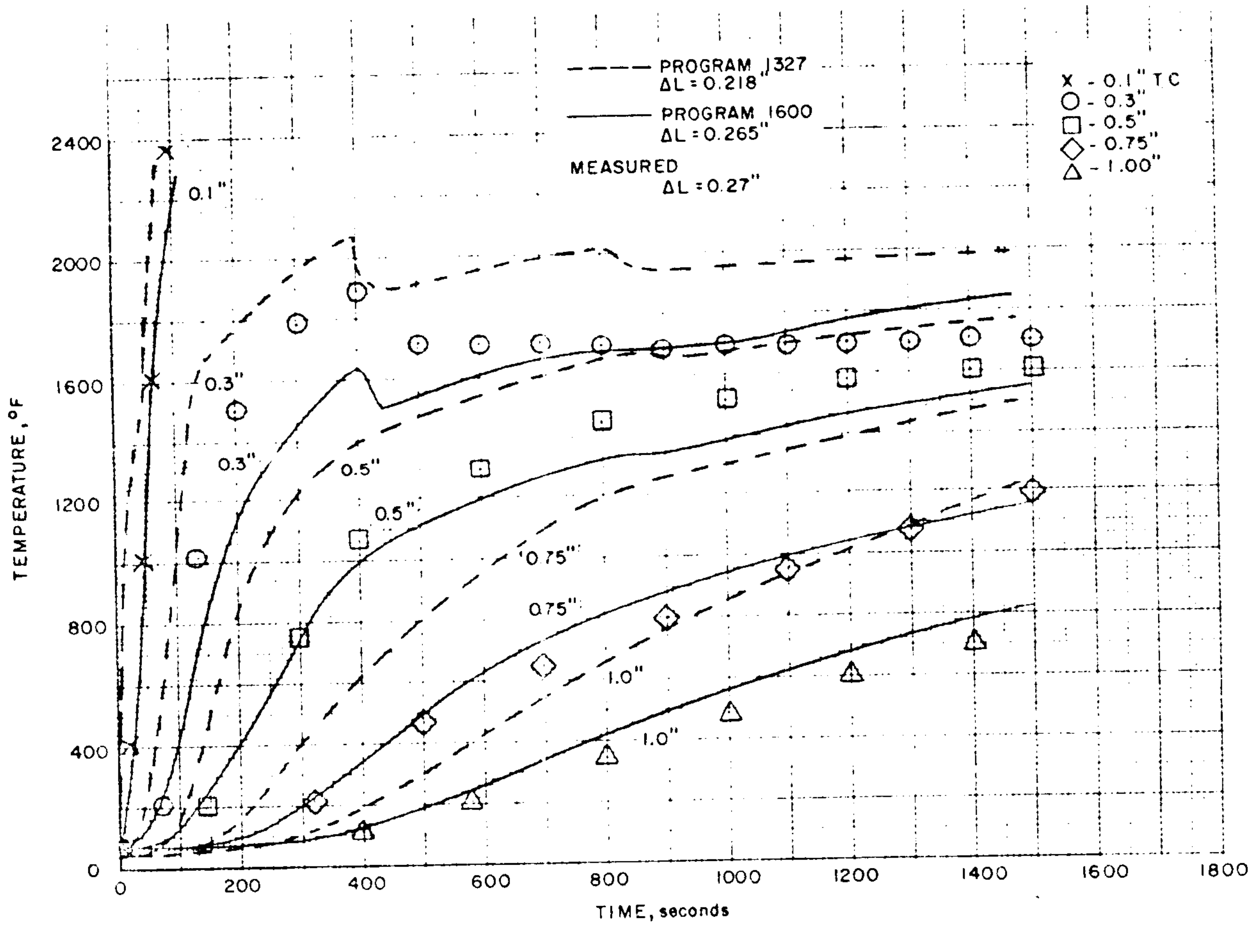

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Figure 2 COMPARISON OF TEMPERATURE HISTORIES IN DEPTH FROM TRAJECTORY SIMULATION TESTS, AVCOAT 5026-39/HC-G

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3.0 ANALYSIS OF THE SCOUT FLIGHT TEST DATA

The analysis of the Scout flight test data was separated into two parts; the first describing the results up to about 480 seconds (last ablation sensor data point), the second describing the results beyond 480 seconds, where only temperature sensor data are available.

3.1 CORRELATION (ABLATION SENSORS OPERATIVE)

3.1.1 Surface Recession and Temperature

An excellent correlation of surface recession and temperature in depth through the heat shield was obtained up through approximately 480 seconds. The results of the surface recession correlation are presented in figure 3; examples of the temperature correlation are shown in figures 4 through 7.

The predicted surface recession through 480 seconds (shown in figure 3) is presented for assumed (constant) ablation temperatures of 4000 and 4500°F values selected for both preflight and postflight analysis. It can be seen that all the ablation data (break wire) and char data (make wire) fall within the span of the two predictions. If only the break wire data are considered, it appears that the true surface temperature for this period was about 4300°F. The make wire results which indicate the time at which the char becomes electrically conducting cannot be used to deduce the location of the true receding surface. However, consideration of the likely char conducting temperature (1200°F or more) and the measured char depth (shown subsequently in figure 10) make it possible to conclude that these sensors also tend to predict an ablation temperature of the order of 4000°F.

Superimposed on figure 3 is the stagnation pressure history as computed from a knowledge of the true flight dynamic pressure history. Since the make and break gages are located near the longitudinal axis (the stagnation point for a true nominal flight) the local pressure at these sensor locations is roughly equal to the stagnation pressure. It is extremely important to observe that the design model correlates surface recession accurately during this period when the local pressure increases to over 3 atmospheres. Reference to figures 4 through 7 shows the equally good correlation between test and predicted temperature in depth. It may be seen that except for the 0.70-inch thermocouple depth, the Design Model predictions match or overpredict the temperature in a manner consistent with previously cited ground test results. The simultaneous correlation of surface recession and temperatures in depth indicate the validity of both the analytical model and the assumptions and inputs used in the model for use on Scout heat shield performance predictions. It is a strong indication that the surface heat balance and the description of internal heat conduction are sufficiently accurate for design purposes. Substitution of artificial recession approximations may

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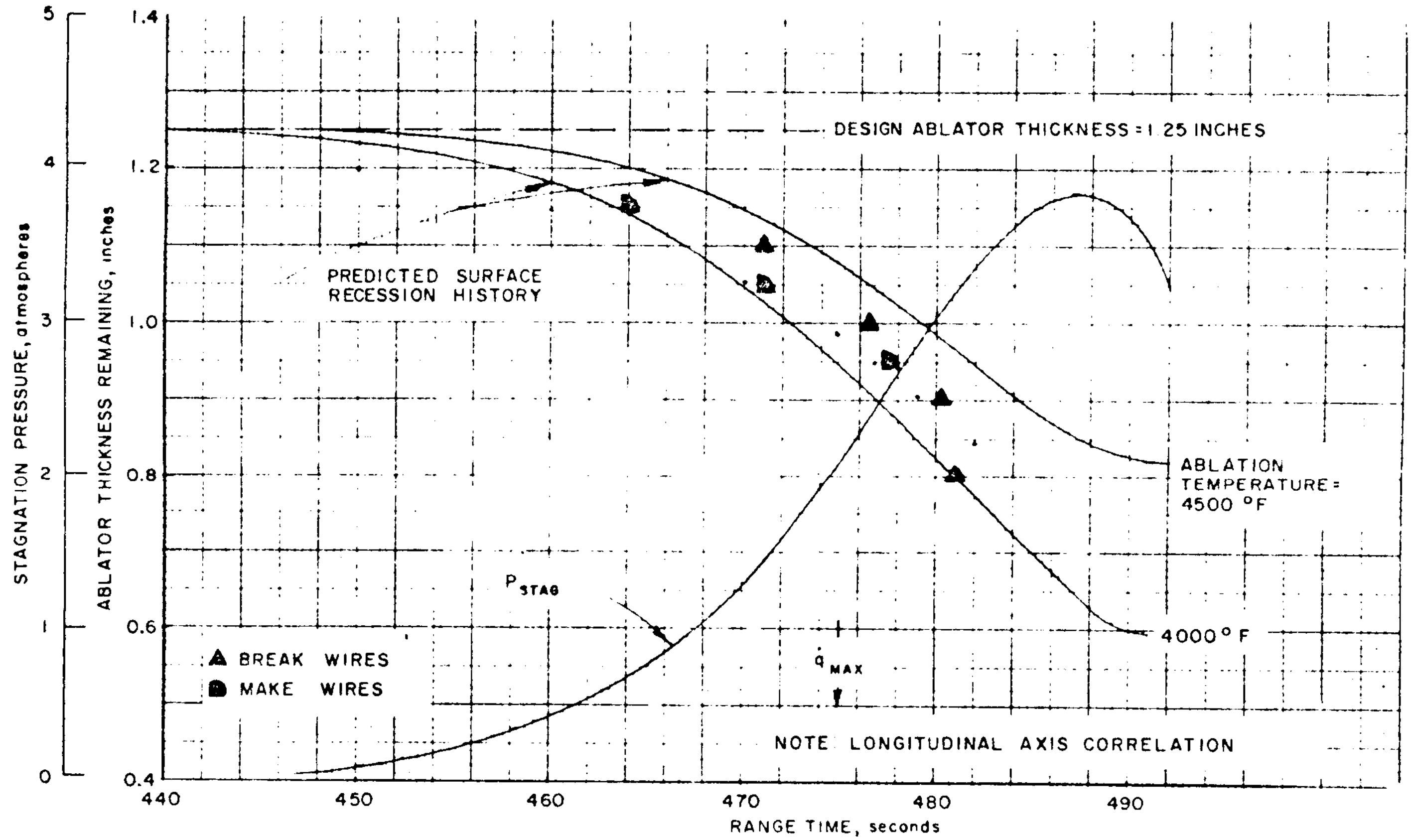

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Figure 3 COMPARISON OF MEASURED (ABLATION GAGE) AND PREDICTED (DESIGN MODEL - 1327) SURFACE RECESSION

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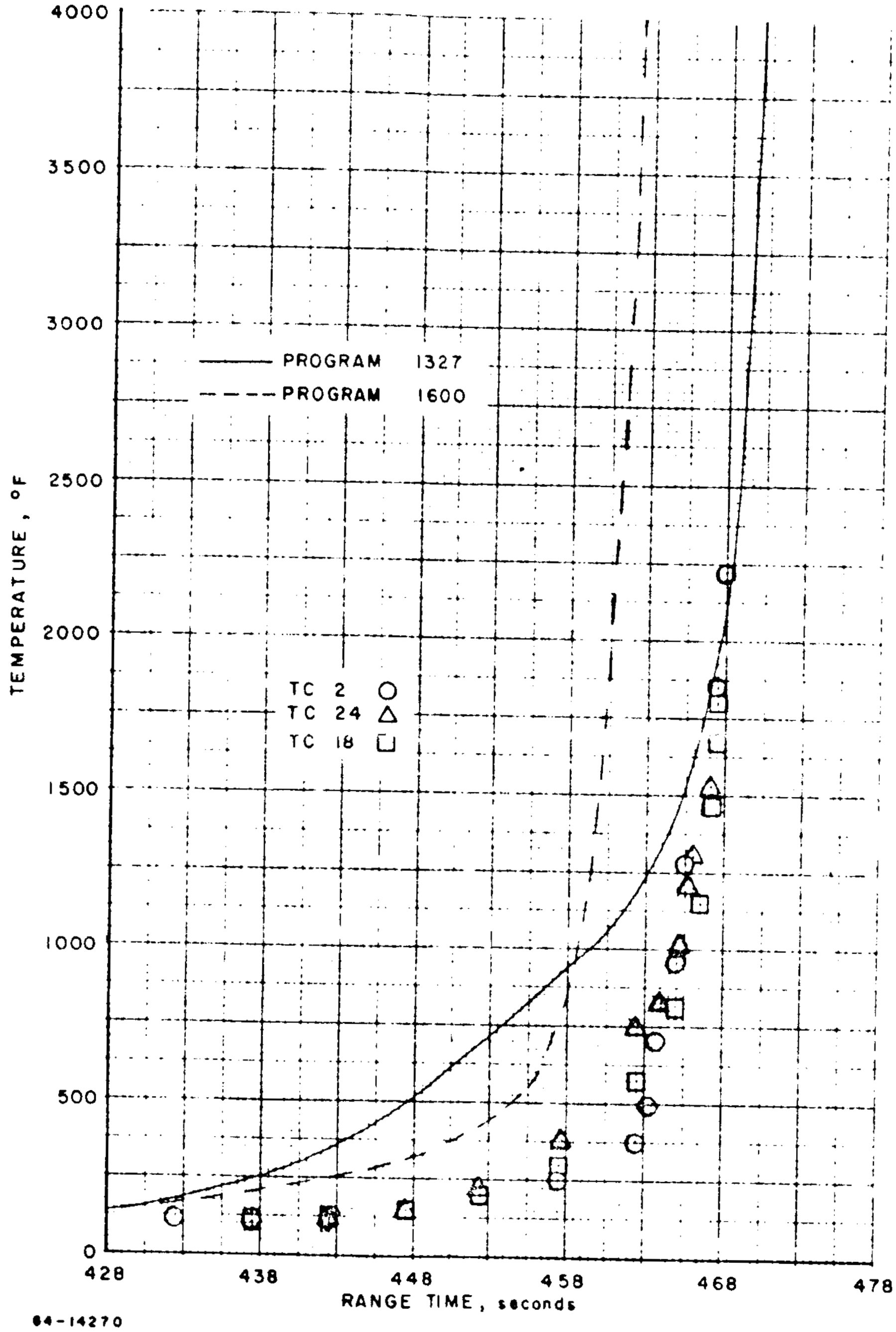

Figure 4 TEMPERATURE HISTORIES 0.2 INCH FROM SURFACE

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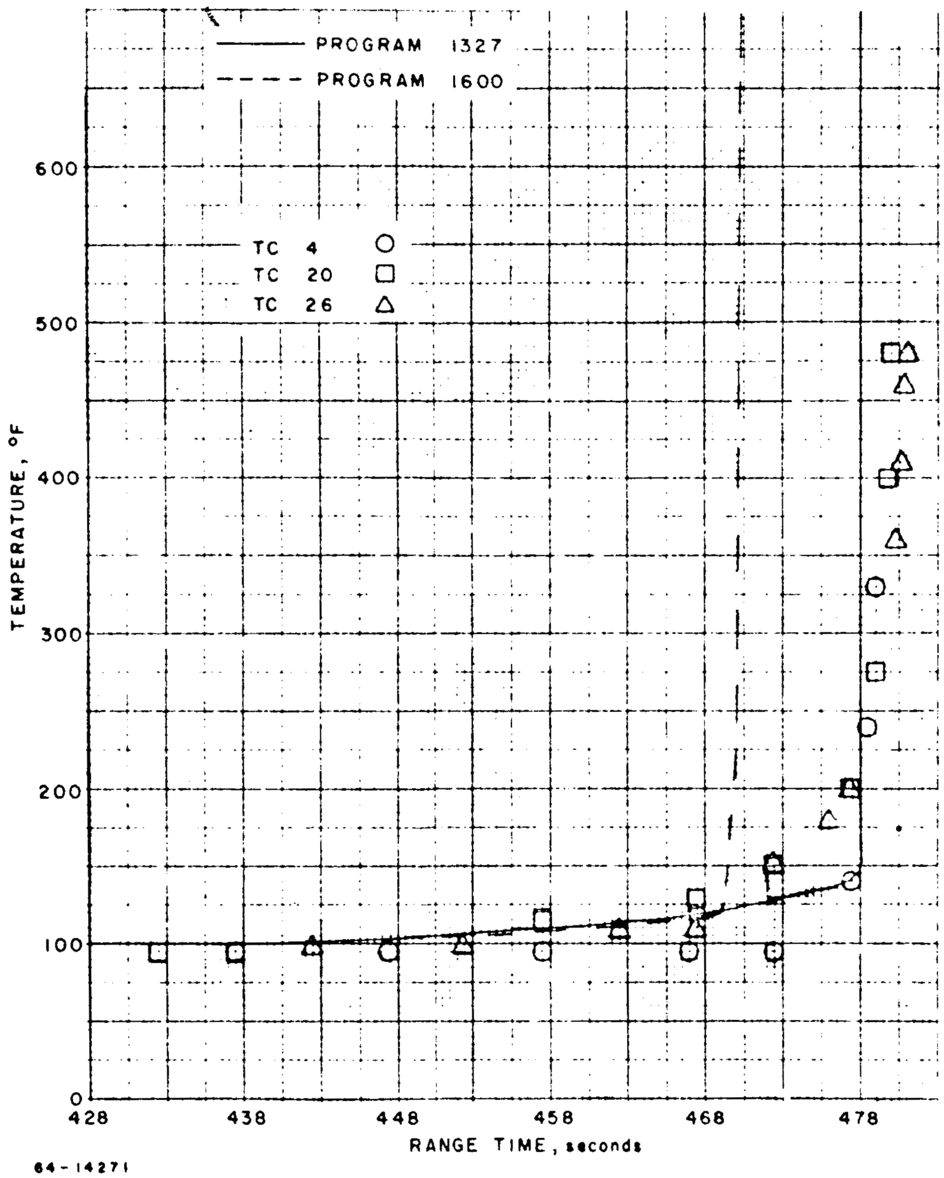

Figure 5 TEMPERATURE HISTORIES 0.4 INCH FROM SURFACE

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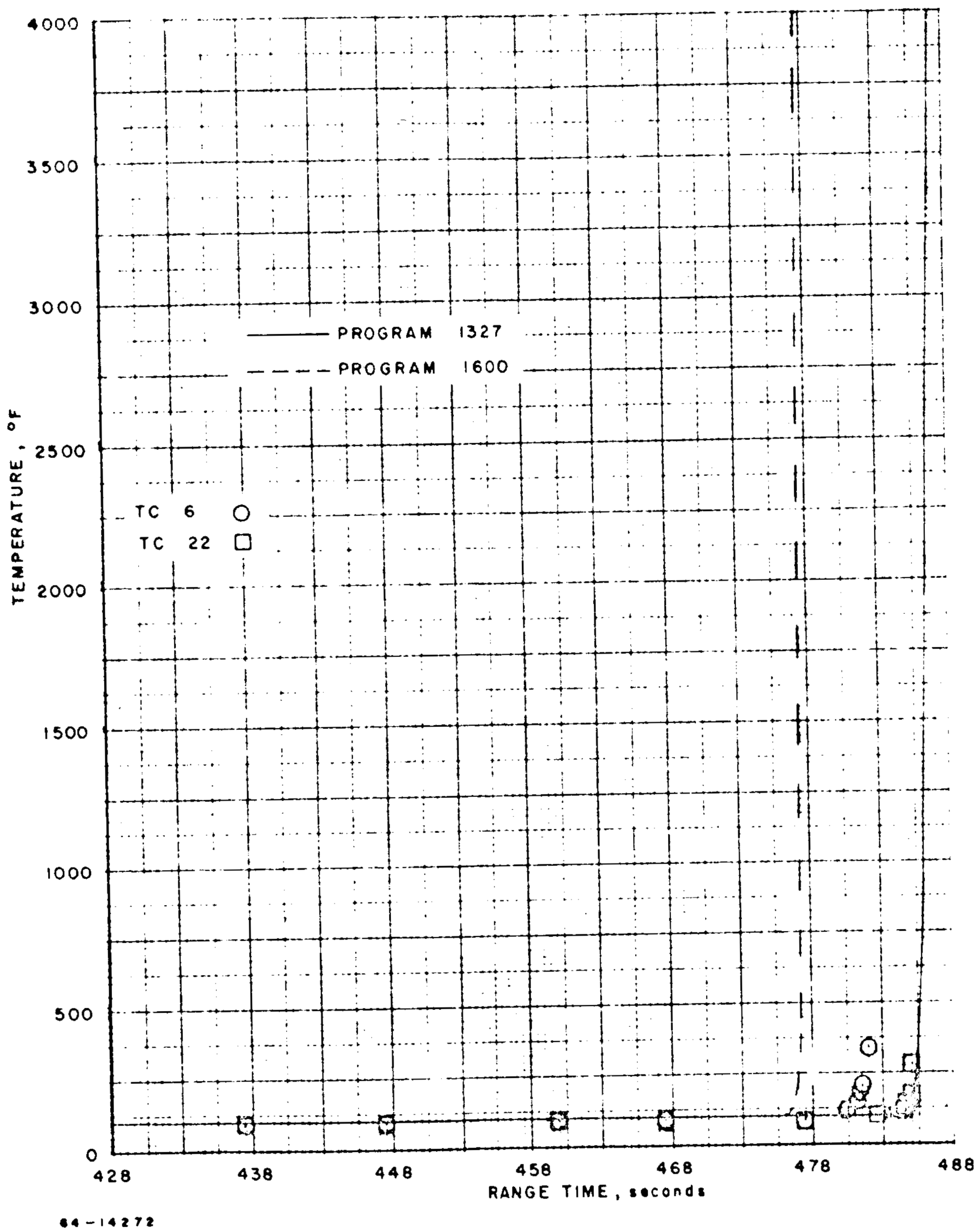

Figure 6 TEMPERATURE HISTORIES 0.6 INCH FROM SURFACE

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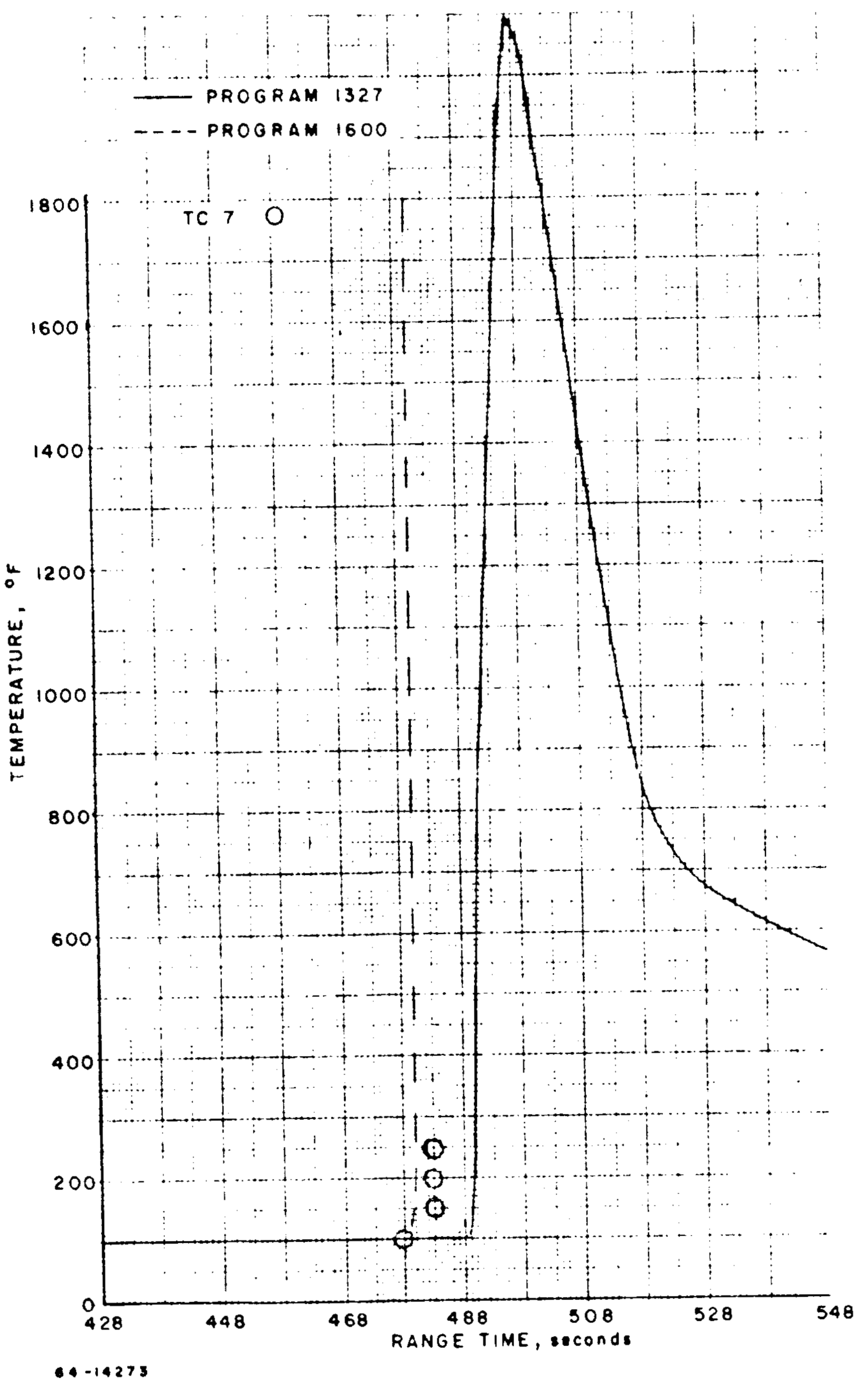

Figure 7 TEMPERATURE HISTORIES 0.7 INCH FROM SURFACE

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upset this heat balance unless compensating errors are made. Proof of any analytical technique requires accuracy in predicting surface recession and temperature in depth simultaneously.

3.1.2 Pressure -- Surface Recession Correlation

The Scout ablator surface recession rate during flight may be correlated with ground test pressure-recession data as shown in figure 8. The ground test correlation as indicated by the solid line was evaluated from steady state ablation tests conducted in the Avco RAD OVERS and Model 500 arc facilities which have a stagnation pressure capability ranging over roughly 3 orders of magnitude (from 10^{-3} to 1 atmosphere). The spread of the ground test experimental data is shown by the bars. Based on this correlation, the 1/2 power relationship between surface recession ($\dot{s}$) and pressure (p) used for the Charring Ablation Model was determined. It should be noted that the peak stagnation pressure for the Apollo HSE-3A (design) trajectory falls within the extremes of the test data while the Apollo HSE-6 (undershoot) trajectory is slightly beyond the Model 500 pressure capability. Similarly, the Scout nominal trajectory peak stagnation pressure is also outside the test data range.

If it is assumed that the ablation temperature for the period up to 480 seconds is 4300°F as deduced previously from flight data, the recession rate parameter for Scout may be plotted as shown (by the circular symbols) on figure 8. These recession data fall below the ground test correlation even up to at least 3 atmospheres. Based on these results, it is apparent that recession predicted by the Charring Ablation Model would exceed that indicated for Scout through the initial phase of the Scout reentry trajectory.

3.2 CORRELATION(ABLATION SENSORS INOPERATIVE)

The analysis of the surface recession after 480 seconds cannot be completed with confidence since no ablation data were measured for depths beyond 0.45 from the original OML. Recession may be inferred from theory or from the measured temperature data nearly all of which is for the outboard thermocouple locations (11° 36' from the longitudinal axis).

3.2.1 Recession and Temperature Data Evaluation

The difficulty of deducing the true ablated depth from temperature measurements (particularly when the indicated temperature is low, i.e., less than 2000°F) is indicated in figures 9 and 10. Figure 9 is a reconstruction of the temperature history predictions shown in figures 4 through 7 along with the predicted response for other depths in the ablator. It is apparent that the temperatures at all depths from 0.50 to 0.90 inch would demonstrate a rapid increase as the receding surface approaches that depth. Without considering the rate of surface recession, the char thickness, and the

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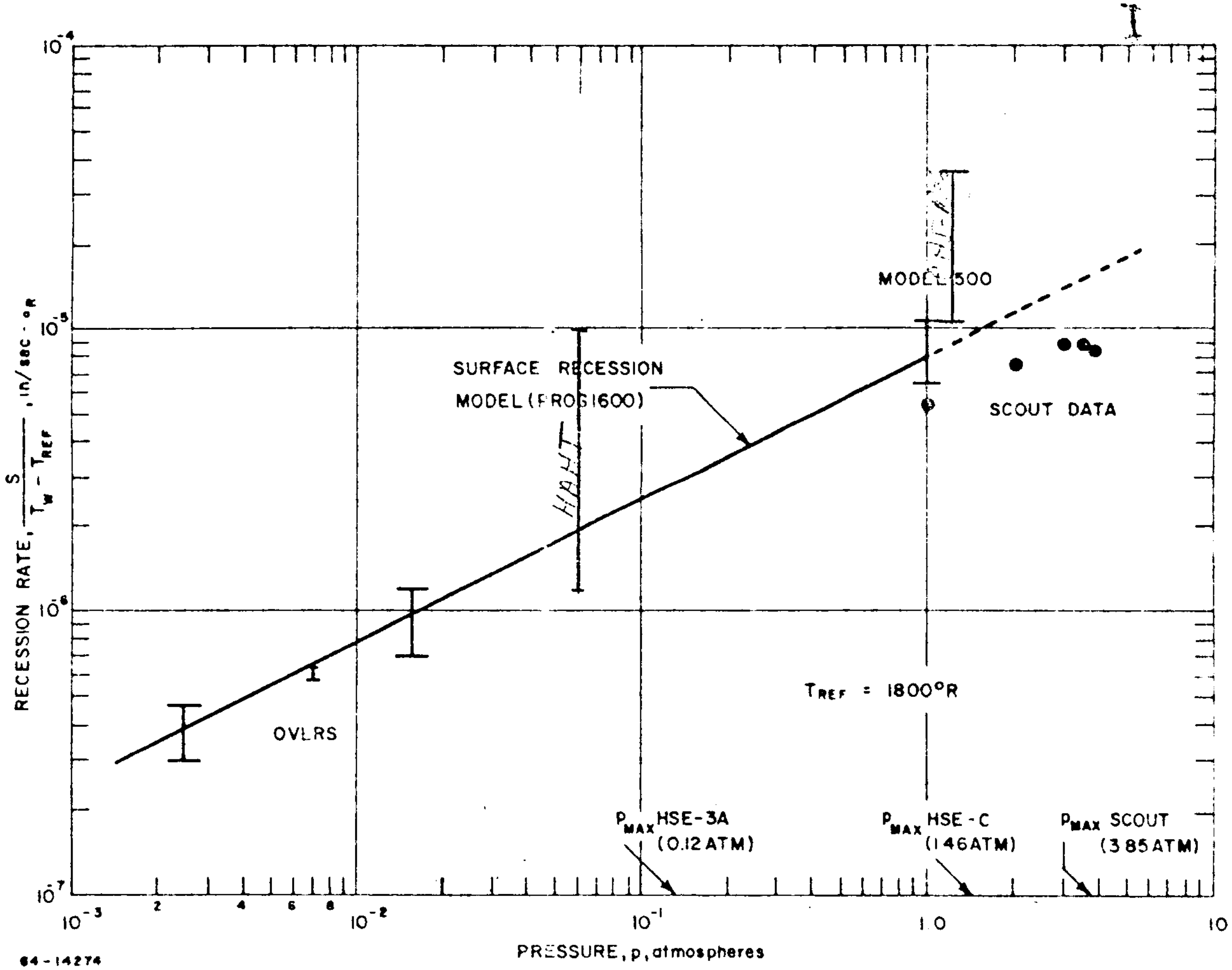

Figure 8 EFFECT OF PRESSURE ON SURFACE RECESSION RATE

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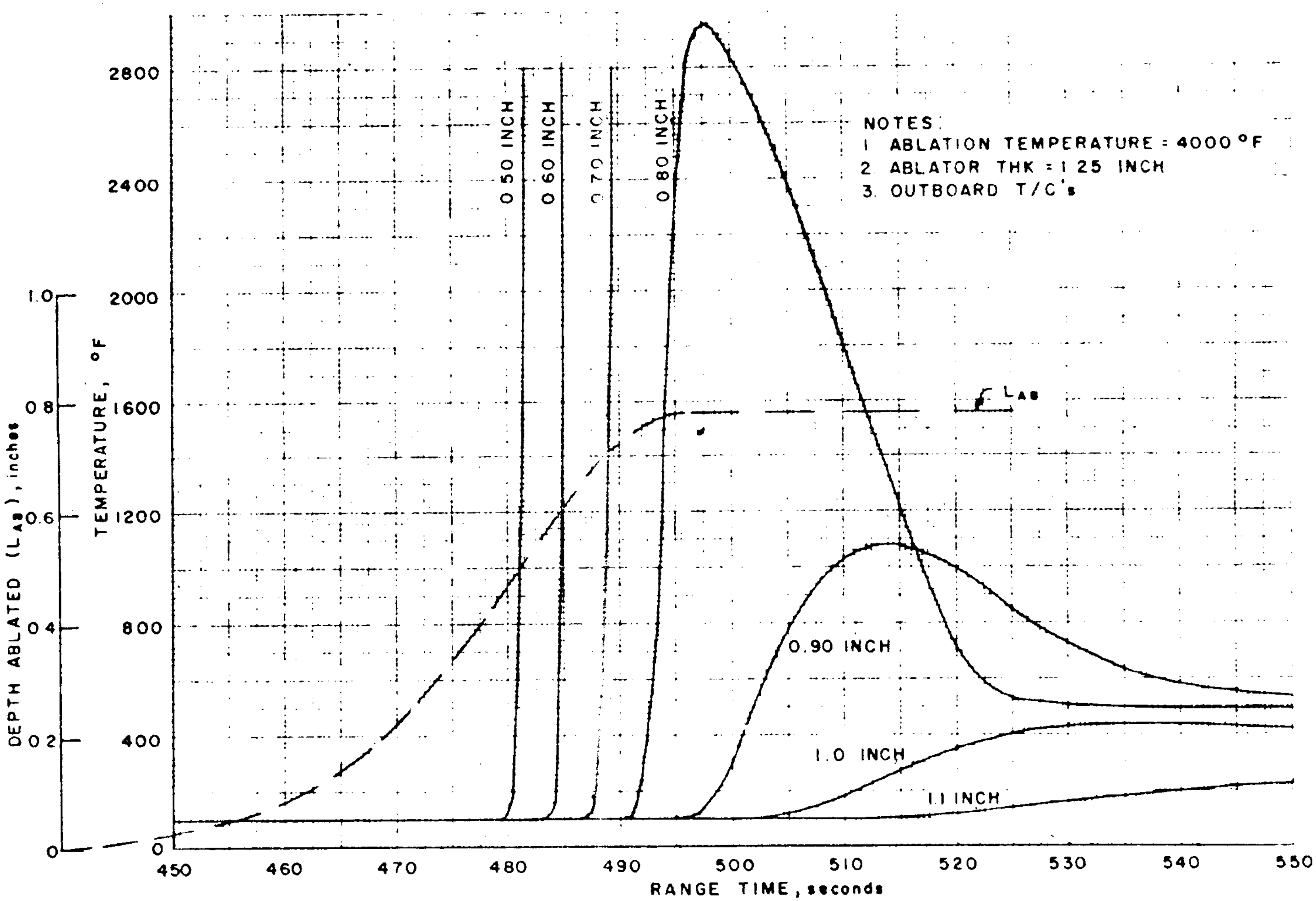

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Figure 9 PREDICTED TEMPERATURE HISTORIES, OUTBOARD THERMOCOUPLE LOCATION

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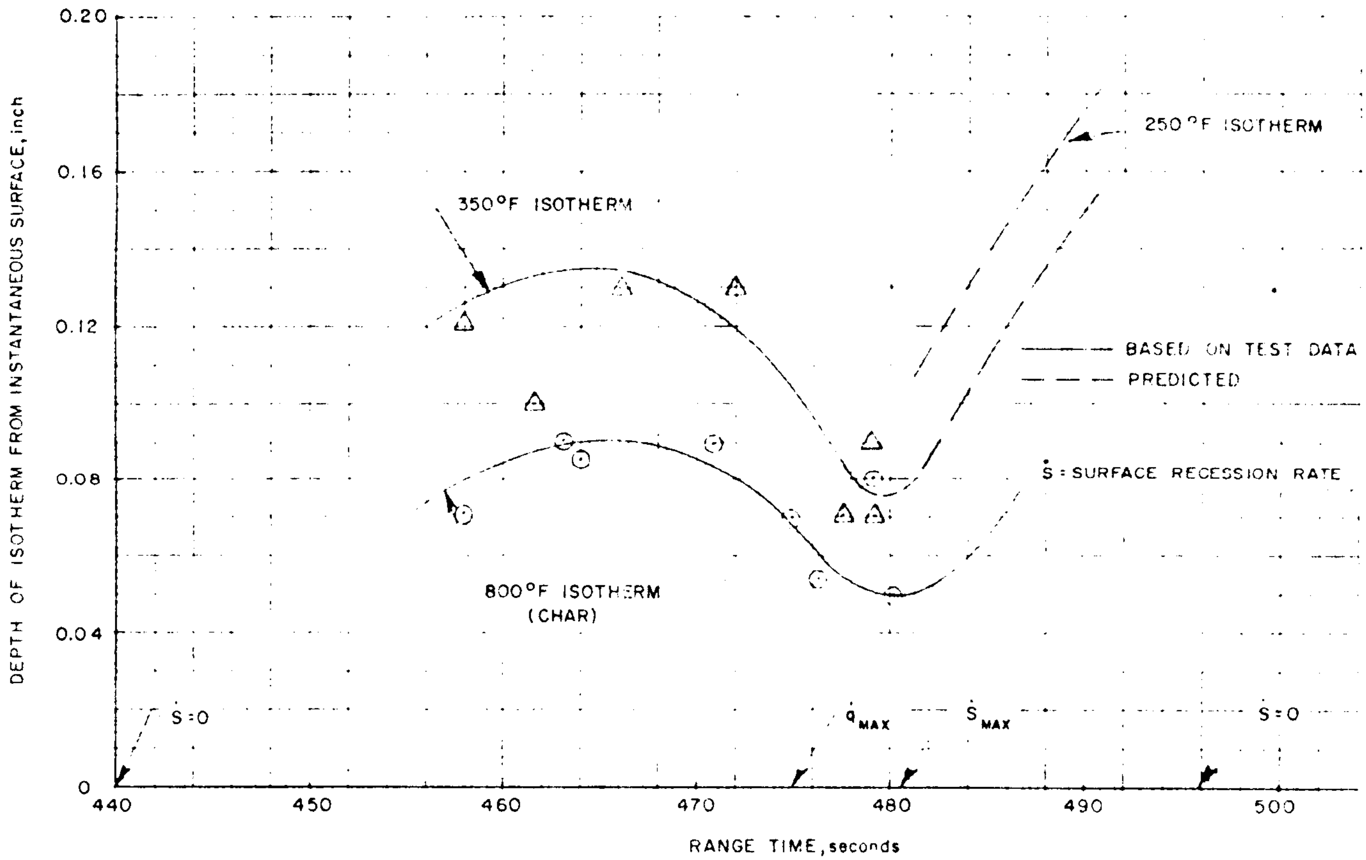

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Figure 10 ISOTHERM HISTORY, SCOUT R-4

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depth of essentially virgin ablator between the char front and a typical isotherm such as 1000 or 250°F, it might be concluded that an indication of rapid temperature rise and the time of surface recession through that depth are synonymous and coincident. The inaccuracy of this assumption may be determined from a comparison of the flight test surface recession (while the ablation sensors were operative) and temperature data as shown in figure 10. This figure presents the penetration depth history of a given isotherm from the true (instantaneous) receding surface. It can be seen that for the Scout trajectory, where the heat flux and enthalpy change rapidly with time, the depth of a particular isotherm changes rapidly with time. For example, assuming that charring takes place at 600°F, it can be seen that the char depth increases early in flight (until the surface begins to recede rapidly) and then begins to decrease as the temperature gradient becomes steeper and the surface recession rate reaches a maximum.* It should be noted that at 480 seconds, the char is about 0.050 inch thick while the distance to the 350°F isotherm is from 0.060 to 0.070 inch which is in fair agreement with flight data. It may be shown theoretically that after peak recession, which occurs roughly from 480 to 481 seconds, the char depth would increase again and would continue to grow even after heating has terminated as the heat diffuses into the remaining uncharred ablator. At ground impact the char depth is predicted to be about 0.15 inch. The depth to the 350°F isotherm location would be approximately 0.20 to 0.25 inch based on Design Model predictions. This estimate is not in good agreement with the test data obtained in flight and indicate sources of error other than thermodynamic description of the ablation and heat conduction process.

The discrepancy between predicted and observed values increases with both flight time and thermocouple location depth. It is coincident with the onset of large angles of attack and suggests two-dimensional ablation and heat conduction effects caused by increased heating at and in the vicinity of the sonic point (rather than accelerated erosion at the "outboard" thermocouple location). With the relatively high ablation rates possible at the corner and two-dimensional internal conduction, it is conceivable that the one-dimensional analysis of the temperature response at TC Nos. 6, 7, 8 would tend to underpredict the temperature response. Consequently, the measured temperatures do not necessarily indicate material removal as might be implied by a strict one-dimensional interpretation of the sensor data. This contention is supported by figure 6 where the response of TC 22 is predicted quite accurately by the one-dimensional analysis, while it is underpredicted for TC No. 6 located at the same depth. The faster than predicted responses of TC 7 and 8 could be explained similarly. Finally the response of TC's 9, 10, 11, and 12 also would be expected to proceed at a much faster rate than predicted by one dimensional model, as the two-dimensional effects would manifest themselves stronger with the elapsed time (and therefore thermocouple location depth).

*This is also borne out by an apparent convergence of the char recession and ablation sensor flight test data.

The second source of the apparent anomaly cannot be disregarded either. Reference is made here to the reliability of the thermocouple readings. In reference 1 the data from TC 10 are discarded due to the apparent instability of the readings prior to "significant" sensor response. However, similar instabilities can be observed in other thermocouples especially TC's 9, 11 and 12. The observed amplitudes of temperature variations prior to rapid change in the rate of temperature increase are, respectively, 30, 50 and 90°F, while for TC 10 it is 140°F. All other thermocouples indicate variations smaller than 50°F; thus one might tend to disregard the information obtained from all four sensors leaving the final surface recession depth entirely in doubt. On the other hand if TC 10 data are considered (along with those of TC's 9, 11 and 12) it may be concluded (see figure 11) that at least 0.25" of ablator was left on the steel substructure until the time of impact. The difference between this possible ablated depth (0.25 remaining) and the one-dimensional response could be attributed to two-dimensional heat transfer effects. It should also be noted that the comparison of responses of TC 9, 11 and 12 are not consistent with each other and thus indicate either flow asymmetries or erroneous readings. Further investigation of the above possible sources of error should be conducted.

The predicted one-dimensional surface recession history at the outboard thermocouple location is shown on figure 12. Only the recession for a 4000°F ablation temperature was considered. Also shown for comparison purposes is the previously presented recession prediction for the longitudinal axis (extended through 490 seconds). The heating history for this outboard location was increased (relative to the nominal heating for this location) by 20 percent during that period when the angle-of-attack exceeded 10 degrees to account for the reduced effective nose radius as the stagnation point shifted off the longitudinal axis. Consequently, the surface recession for the outboard thermocouple location is 0.78 inch compared to 0.65 inch at the longitudinal axis.

Also shown on figure 12 is the predicted recession at the outboard thermocouple location assuming transition at 482 seconds. Calculation of the Reynolds Number history for the true flight condition reflecting the large angle-of-attack from 450 to 500 seconds indicates the results shown in figure 13. It can be seen that, although transition (as defined by a Reynolds Number of 150,000) is unlikely for the zero-angle-of-attack case, transition may occur for the true flight condition after about 482 seconds. Even though the ablation performance of Avcoat-type materials is strongly dependent on the nature of the flow (laminar or turbulent), the net effect on the Scout surface recession history is small due to the simultaneous rapid decrease in enthalpy and heat flux after 480 seconds.

The previous discussion indicates that a reasonable doubt exists concerning the final location of the heat shield surface at the time of impact and that further analysis is required to clarify the problem.

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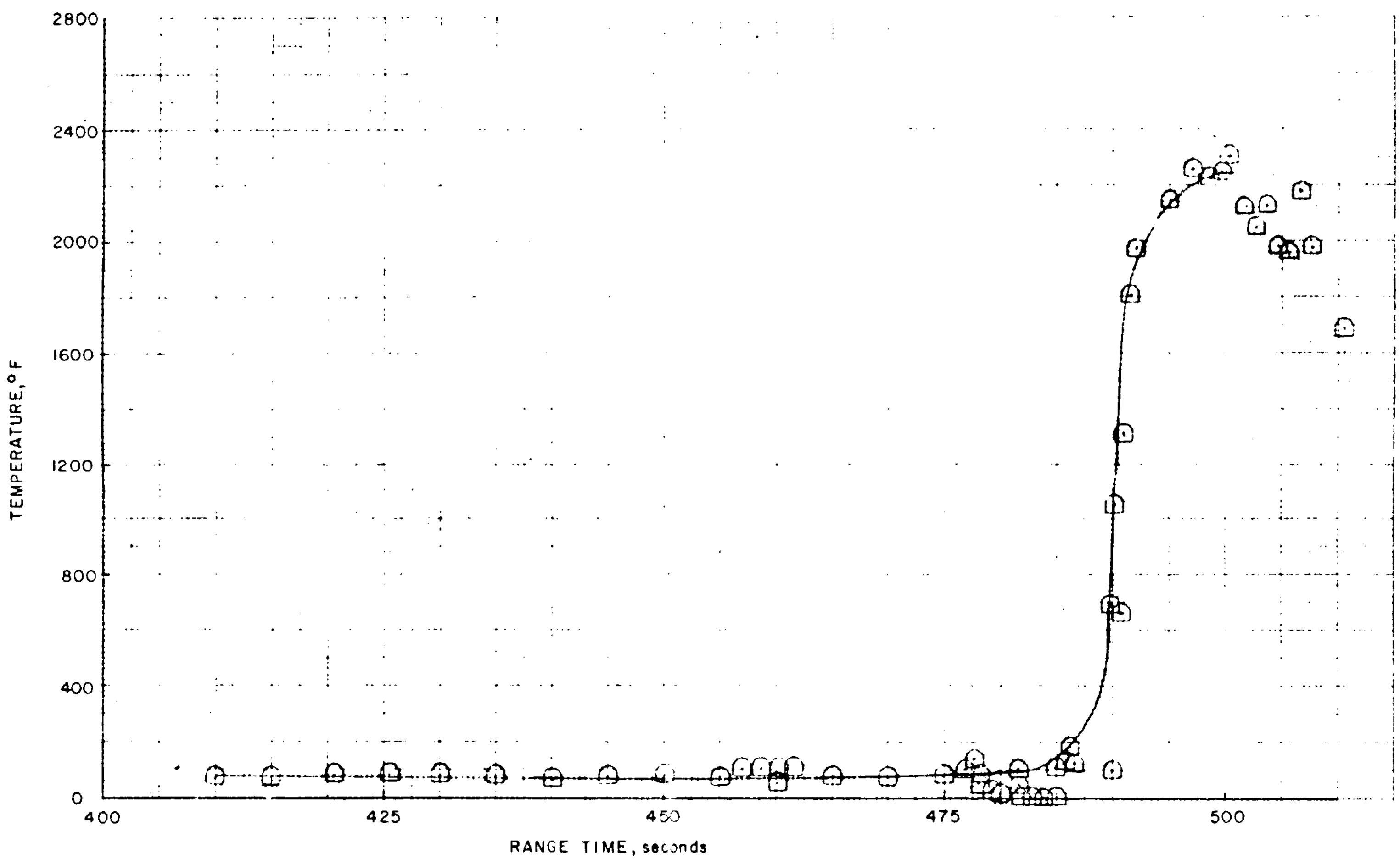

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Figure 11 EXPERIMENTAL TEMPERATURE HISTORIES, THERMOCOUPLE 10-DEPTH = 1.0

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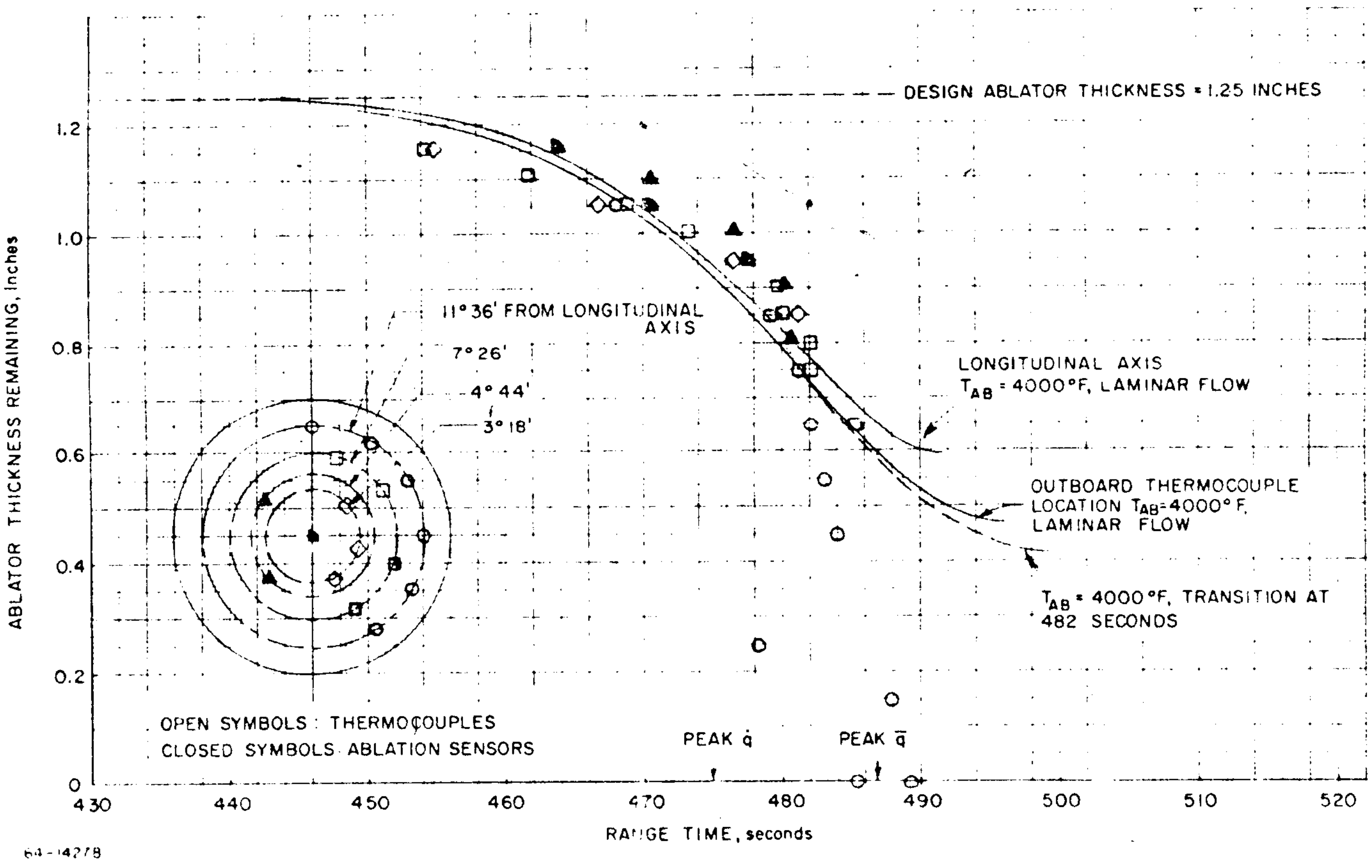

Figure 12 COMPARISON OF ALL SCOUT R-4 DATA AND DESIGN MODEL (PROGRAM 1327) SURFACE RECESSION PREDICTIONS, ABLATOR: AVCOAT 5026-39/HC-G

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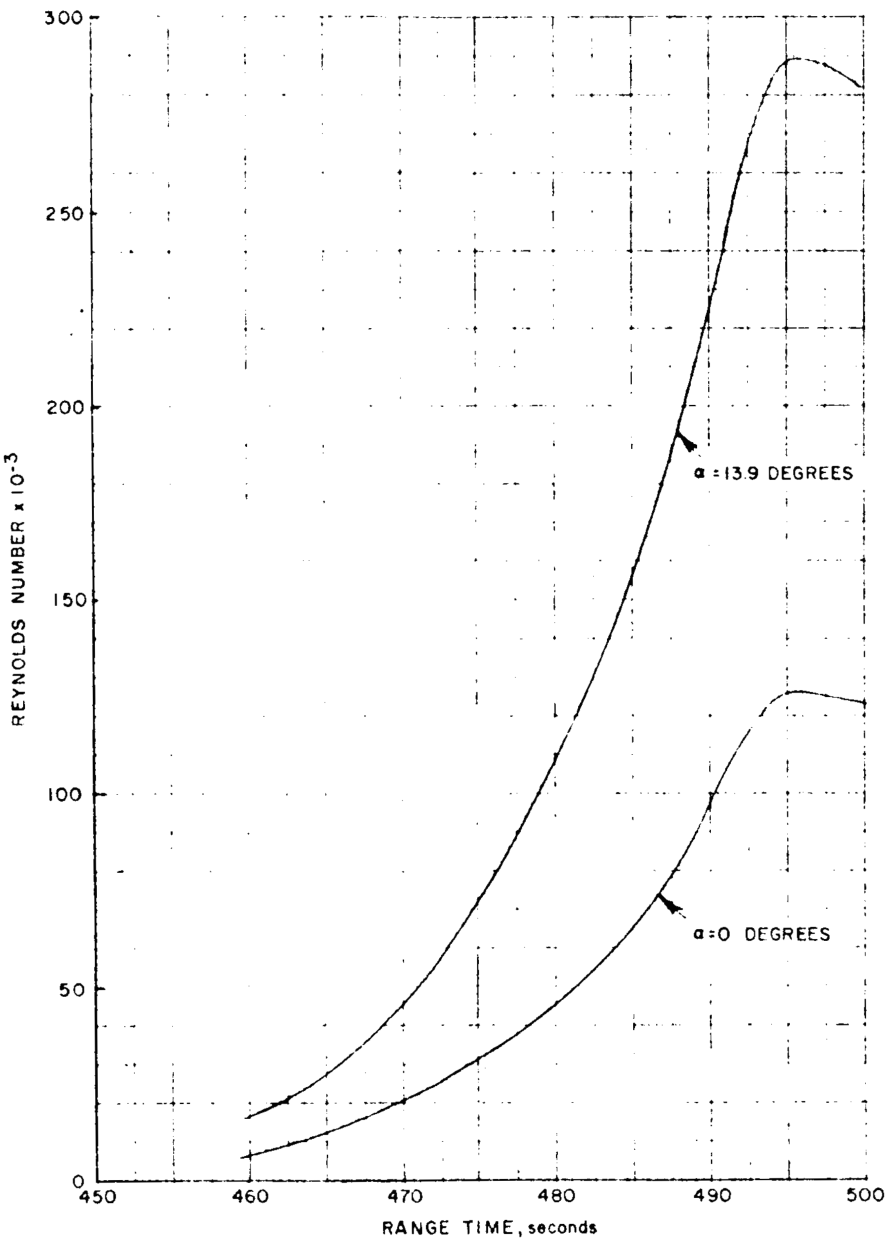

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Figure 13 WETTED LENGTH REYNOLDS NUMBER FOR OUTBOARD (11°36') THERMOCOUPLE LOCATION

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4.0 SIGNIFICANCE OF SCOUT DATA FOR APOLLO

It has been shown that good correlation of temperature and surface recession data was achieved (using the standard Apollo Heat Shield Design Technique) significantly past the time of peak heating for Scout and during the period in which the local pressure increased to 3 atmospheres. When applied to Apollo, these facts tend to increase the confidence in the present heat shield design.

4.1 COMPARISON OF REENTRY ENVIRONMENTS

A careful study of the environmental parameters associated with Scout reentry and Apollo reentry leads to the conclusion that Scout reentry conditions are: (1) at least a factor of 2 more severe than the most severe Apollo reentry (the undershoot entry)trajectory , HSE-6, and (2) at least a factor of 10 more severe than the Apollo design trajectory, HSE-3A.

Shown in table II are the heat flux, shear, pressure, and enthalpy and Reynolds number at peak heating and peak dynamic pressure for Scout R4 and the two Apollo trajectories. Figure 14 shows the correlation of Re versus H/RT_0 for the same trajectories. The comparison is made for Station 222 for Apollo, which is the most critical design location, and for $s/s^* = 0.95$ which is near the outboard thermocouple location for Scout. It is immediately evident from these data that the Scout R-4 trajectory is more nearly like the Apollo HSE-6 trajectory than HSE-3A, being roughly comparable in heat flux but having 3 times the shear and twice the peak stagnation pressure. Also significant is the fact that the enthalpy at peak heating and peak dynamic pressure is at least a factor of 2 greater for both Apollo trajectories than for Scout. This latter point has a particularly strong significance since the ablator performance varies linearly with enthalpy. Whereas the Scout R-4 trajectory may be considered a reasonable (a factor of 2 or 3 more severe) simulation of the Apollo emergency entry trajectory, the Scout environment is at least a factor of 2.5 in heat flux, 10 in shear, 30 in pressure and 2 in enthalpy more severe than the peak values for the Apollo design trajectory (HSE-3A). It may further be seen that the tendency for transition in the critical heating portion of the trajectory is more likely for Scout than for either of the Apollo trajectories although at peak heating the Reynolds Number is subtransition for all three trajectories.

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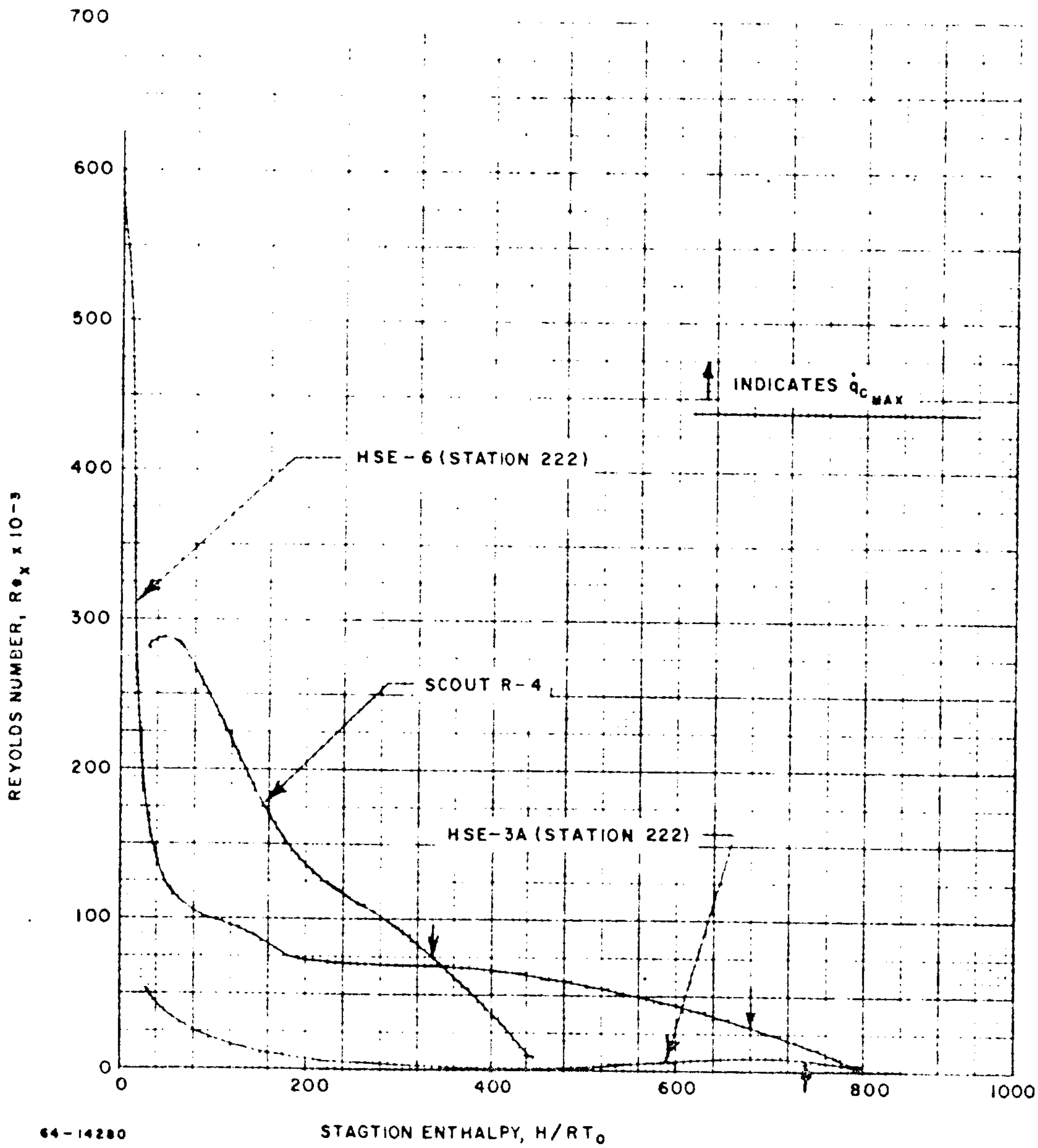

Figure 14 REYNOLDS NUMBER ENTHALPY RELATIONSHIP

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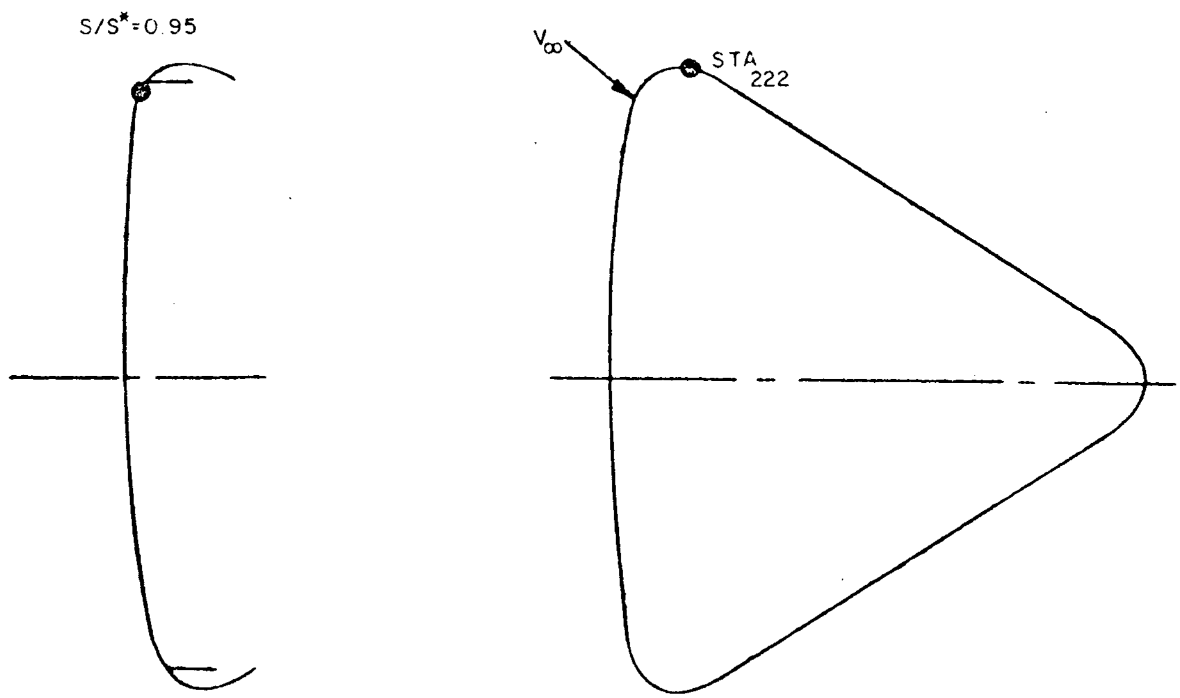
TABLE II

COMPARISON OF REENTRY ENVIRONMENT SCOUT R-4 AND APOLLO

Parameter	Scout R-4 (Nominal) $s/s^* = 0.95$	Apollo HSE-3A Sta 222	Apollo HSE-6 Sta 222
Maximum Heat Flux (q_{max}), Btu/ft^2-sec	820	327	770
Maximum Shear, lb/ft^2	31	3.0	8.05
Maximum Stagnation Pressure, (q_{max}), atmos.	3.75	0.12	1.46
Stagnation Enthalpy, Btu/lb			
q_{max}	11,400	24,500	20,800
q_{max}	5,200	23,400	18,800
Reynolds Number			
q_{max}	72,000	5,800	43,600
q_{max}	184,000	5,500	48,800



SCOUT R4

APOLLO

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4.2 HEAT SHIELD DESIGN AND PERFORMANCE COMPARISON

A review of the Apollo design philosophy is required before investigating the possible influence of Scout data on the Apollo design. A comparison of Apollo design performance for both the design trajectory (HSE-3A) and HSE-6 is shown in table III. For five characteristic body stations on the aft compartment and toroidal corner section, the total heat load, required ablator thickness, surface recession, and substructure temperature are shown. It is evident that although the magnitude of the reentry environment parameters (heat flux, shear, and pressure) is more severe for HSE-6 than HSE-3A, the ablator thickness requirement is dictated by the total heat load as defined for HSE-3A. In fact the local ablator thickness requirement for HSE-3A is roughly 3 times that required for HSE-6. Furthermore, the total predicted surface recession for HSE-6 is generally less than that indicated for HSE-3A.

Since the data presented in table II are based on the Design Model which, when compared with ground test flight simulation results indicate conservatism in temperature while predicting recession, and since the same analytical technique has been used to correlate the Scout data at least through the period of interest for Apollo, it is apparent that there will be no change in the Apollo design.

If, however, for the purpose of argument, the surface recession is forced to follow the temperature measurements from 480 to 490 seconds by arbitrarily degrading the ablation characteristics used in the design model, the ablation prediction for HSE-6 will be altered accordingly. The results for HSE-6 of this arbitrary reduction in heat of ablation are shown in figure 15. It can be seen that the net effect is a 0.050 inch increase in the predicted ablation to thickness. Because the Apollo heat shield is vastly overdesigned in terms of total ablator thickness requirement for HSE-6, an increase in ablation of 0.050 inch would have a negligible effect on the design confidence or conservatism. It should be noted, that while the design ablator thickness is 2.44 inches, the total predicted surface recession is only 0.42 inch.

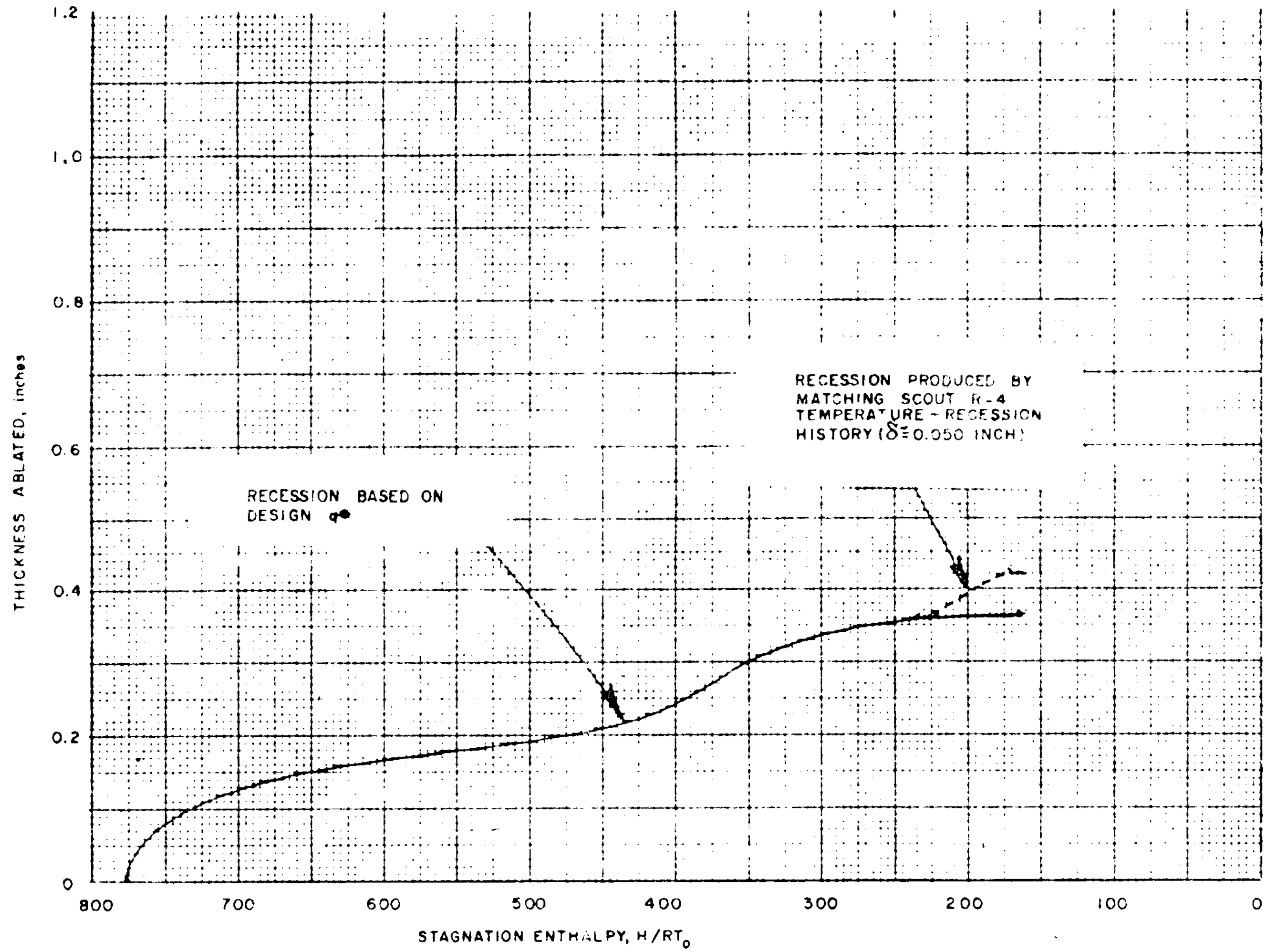

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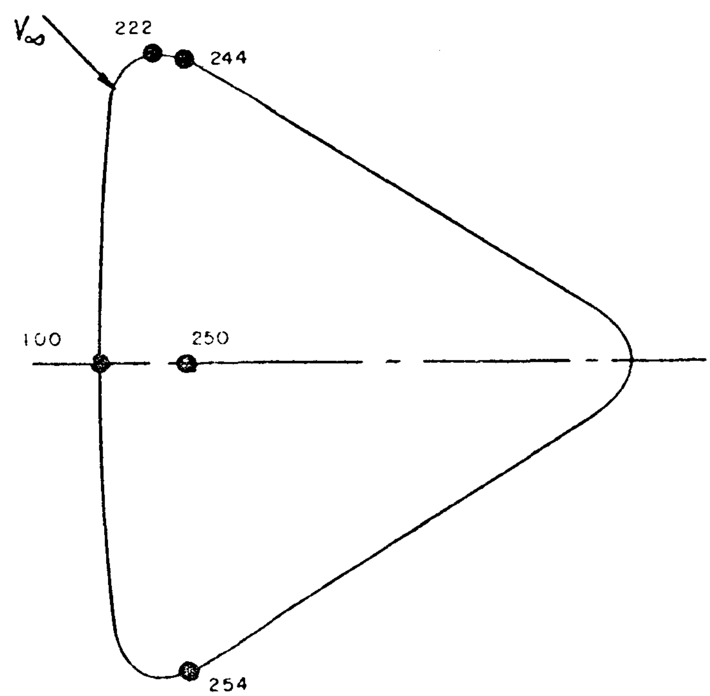
Figure 15 SURFACE RECESSION FOR HSE-6 STATION 222

TABLE III

HEAT SHIELD DESIGN AND PERFORMANCE COMPARISON
HSE-3A AND HSE-6

Body Station	Heat Load, Btu/ft^2	Ablator Thickness Req. Inch	Surface Recession, Inch	Substructure Temperature, °F
HSE-3A				
100	32,350	1.54	0.13	600
222	107,600	2.44	1.26	600
244	31,850	1.80	0.11	600
250	6,450	1.16	0.001	600
254	1,100	0.87	-	600
HSE-6				
100	16,900	(0.55)*	0.15	150
222	30,000	(0.80)	0.36	250
244	8,950	(0.50)	0.05	250
250	2,350	(0.40)	0.01	290
254	350	(0.15)	-	285

( )* Since heat shield is sized for HSE-3A, thicknesses shown for HSE-6 are thoeretical requirements.



[redacted]

5.0 SUMMARY AND CONCLUSIONS

A postflight evaluation of the Scout R-4 flight was conducted to obtain correlation parameters which could be used to substantiate the Apollo heat shield design. Surface recession predicted by the design technique (for an assumed ablation temperature of 4000°F) was in good agreement with measured ablation results up to the time of peak heating during which the pressure increased to roughly 3 atmospheres. Good agreement also was obtained between predicted and measured temperature for those thermocouples located from 0.20 to 0.70 inch from the ablator OML.

Surface recession predictions for the outboard thermocouple location, while being 33 percent greater than at the longitudinal axis, indicate a total ablated depth of about 0.78 inch. Predictions of temperatures in depth were in good agreement with the measured values except for those thermocouples located within 0.45 of the substructure at late flight times. Based on the general agreement between surface recession and temperature prior to 480 seconds, recession after 480 seconds was inferred.

Design conservatism is indicated throughout that portion of the trajectory which is immediately applicable to the Apollo emergency entry trajectory (HSE-6). By forcing a reduction in the established heat of ablation-enthalpy relationship to match the Scout temperature-ablation history from 480 to 490 seconds, the Scout data may be applied directly to Apollo. Using arbitrarily degraded ablative performance parameters (H_V and η) for an analysis, the predicted ablation depth for the Apollo heat shield for HSE-6 flight would increase approximately 0.050 inches. Because of the inherent overdesign condition for HSE-6 relative to HSE-3A, the Apollo design trajectory, no heat shield redesign is required. In fact, the correlation for the Scout flight as produced by the design model tends to increase the confidence in the Apollo heat shield design. Based on the above analysis of Scout R-4 flight test, the following conclusions may be reached:

1. Good agreement between the ablation and char recession sensor measurements and theoretical predictions was obtained during the period of their functioning.

2. Good agreement between the measured temperature response and prediction was obtained for the inboard thermocouple locations.

3. The outboard thermocouple measurements agree relatively well with predictions during the period of ablation sensor functioning and prior to advent of large angles of attack, at which time the agreement deteriorates.

4. It is believed that the outboard thermocouples displayed symptoms of instability similar to that observed in TC 10 disqualified in reference 1. Further examination of reliability of these thermocouples appears to be in order, as well as two-dimensional analysis of the expected thermocouple response at these locations.

[redacted]

5. The prediction of surface recession-pressure relationship derived from the ground test data is generally conservative and especially at pressures greater than 1 atm.

6. Apollo heat shield design procedure is verified under much more severe flight conditions than those expected for Apollo flight trajectories.

7. Serious doubt exists concerning use of temperature sensor "last smoothly rising temperature" data points as indication of surface recession based on one-dimensional theory.

8. Direct use of "upper bound" recession data as determined by temperature sensor readings does not indicate any requirement for Apollo heat shield design change.

[redacted]

6.0 REFERENCES

1. Raper, J. L., Preliminary Results of a Flight Test of the Apollo Heat Shield Material at 28,000 Feet Per Second, Langley Working Paper No. 54 (27 October 1964).

2. Munson, T. R. and R. J. Spindler, Transient Thermal Behavior of Decomposing Materials, Part I, presented at 30th IAS Annual Meeting (January 1962).

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